Meeting Summary

Ocean Acidification: Setting Water Quality Goals
Uncommon Dialogue
October 17-18, 2016
Stanford University

Hosted by:
Stanford University's Woods Institute for the Environment and the Center for Ocean Solutions, the California Ocean Protection Council, and
The Southern California Coastal Water Research Project Authority

Table of Contents

Executive Summary

In response to the West Coast Ocean Acidification and Hypoxia Science Panel's Recommendation 3 (Revise water quality criteria), 25 experts were convened at Stanford University on October 17-18, 2016 to chart a path toward development of ocean acidification (OA) water quality goals. Participants were asked to help develop goals that in the short term could be used as management tools for defining monitoring needs and for interpreting modeling and monitoring output, and in the longer term could form the foundation for water quality criteria.

The workshop had three objectives: 1) Identify the chemical parameters and biological indicators that are most appropriate for assessing the status of ocean acidification; 2) Prioritize the research needed to advance the parameters and indicators toward use as water quality goals; and, 3) Pinpoint the biggest impediments to development of criteria from these goals and actions that can be taken to lessen those impediments.

Top parameters and indicators for developing ocean acidification water quality goals

Participants identified **pH** and **carbonate saturation state** as the two chemical parameters that are the most likely candidates for near-term adoption as water quality goals. They reached this conclusion because ~~these parameters~~pH or the parameters used to calculate carbonate saturation state are readily measureable using available technology, they have been documented through both laboratory and field studies to affect biota, and their widespread use in ongoing monitoring programs provides context for how these parameters vary naturally in the ocean environment.

They also identified **pteropod shell condition** as the most likely biological indicator for near-term application. Pteropod shell condition rose above other candidate biological indicators because pteropods are widely distributed, methods to measure their shell condition are standardized and readily transferable to non-specialists, and shell condition has been linked to organism growth and survival. Pteropod population trends are also predictive of higher-level ecosystem effects and therefore shell condition represents a measurable early-warning indicator.

Commented [1]: I'm uneasy about this blanket statement and would prefer more nuanced phrasing that acknowledges that other candidate taxa might be viable also, as is discussed more concretely in the body of this document. I don't think we want to imply in the Executive Summary that pteropods will be the silver bullet of biological monitoring. They are likely to be great, yes, but will have limitations in addition to advantages, just as other species do.

Commented [2R1]: I agree; I think we should say that three taxa were prioritized: pteropods, oysters and rockfish.

Priority research needs

Participants recognized that the recommended chemical parameters and biological indicators are not yet sufficiently advanced for use as defined management goals or as criteria, so they developed research recommendations that would enhance their application. The top research recommendations were similar for both chemical parameters and biological indicators:

1) **Expand the linkage between chemical exposure and biological response**. In order to establish biologically-relevant WQ goals, the linkage of chemical exposure and biological response must be established~~This is necessary to establish well-~~

Commented [3]: This needs to go first

~~defined parameter or indicator thresholds~~. Participants identified that this should be initiated through literature review and integration of studies conducted to date, focusing on the three major taxa (Pteropod, oysters, rockfish) for which data are readily available. ~~.~~

~~1)~~2) **Define natural variability in the parameters**. Marine organisms have tolerances of pH and carbonate saturation state outside of their optimum range. ~~Identifying and quantifying~~Quantifying the frequency and duration of “natural” fluctuations in OA chemical parameters fluctuations, without the influence of ~~change in ocean acidification requires differentiation between natural fluctuations and fluctuations due to~~ anthropogenic ~~activities~~a, is an important element of OA WQ goal setting.

~~2)~~3) **Standardize operating procedures for measuring the parameters and indicators**. Many existing procedures require complex research techniques. Managers cannot use chemical parameters or biological indicators to identify and quantify changes in ocean acidification until they can be consistently measured by users with a wide range of experience.

~~3)~~1) ~~**Expand the linkage between chemical exposure and biological response**. This is necessary to establish well-defined parameter or indicator thresholds. Participants identified that this should be initiated through review and integration of studies conducted to date.~~

4) **Support co-located chemical and biological field measurements.** Most threshold development work is presently being conducted through laboratory exposure experiments and there is a need for appropriate field data to validate laboratory observations.

Impediments to new criteria

Workshop participants identified four primary impediments to developing new regulatory criteria. In addition to the research needs identified above, participants noted the following needs:

1) **Clearly establish the management need for new criteria.** Water quality m~~M~~anagers indicated they are only interested in deploying the resources needed to develop OA water quality criteria if they are convinced that local nutrient and carbon inputs are a meaningful contributor to local acidification conditions and that local management actions would have a meaningful effect. Participants identified coupled physical-biogeochemical models that allow distinction of local and global emission effects as an appropriate means to ~~address this need~~assess the contribution of nutrients.

2) **Generate the motivation and resources required to conduct the necessary science and administer the criteria implementation process.** Participants noted that the cost for these activities will likely exceed $10M—a price tag that requires broad public and legislative support. While achieving that is inherently a nonscientific activity, scientists can assist by better connecting acidification impacts to species and ecosystems of public concern.

Commented [4]: I don’t think this data is available for most organisms. Most studies have used current and future conditions, and the response curve or functional relationship is widely unknown.

Commented [5]: I agree with Kristy on this. A recommendation that implies that the data already exist to infer thresholds/tipping points for most organisms would be misleading.

Commented [6]: If this word is meant to define variability it doesn’t do the trick. Variability is better.

Commented [7]: We are not defining natural variability for the sake of source attribution; we are doing it because we need to understand the natural exceedance frequency in which ocean waters would experience occasional deviations from lab-derived thresholds. This variability is what the organisms are adapted/resilient to. This was a key point of Francis’ talk.

Commented [8]: I don’t think this data is available for most organisms. Most studies have used current and future conditions, and the response curve or functional relationship is widely unknown.

Commented [9]: I agree with Kristy on this. A recommendation that implies that the data already exist to infer thresholds/tipping points for most organisms would be misleading.

Meeting Background, Goals and Overview

Background

Oceans absorb approximately one-third of global carbon dioxide (CO_2) emissions. While the ocean's role in absorbing CO_2 has helped mitigate the effects of emissions on earth's climate, it has caused fundamental changes in ocean chemistry through a phenomenon known as ocean acidification (OA). While OA remains a global challenge, emerging research indicates that the West Coast of North America will face some of the earliest and most severe effects to its coastal ecosystems and the humans that depend on them.

In 2013, the California Ocean Protection Council charged the California Ocean Science Trust with establishing the West Coast Ocean Acidification and Hypoxia Science Panel, comprising 20 leading scientific experts from California, Oregon, Washington, and British Columbia. The panel summarized the current state of knowledge on OA and hypoxia (OAH) and developed scientific consensus about available management options to address impacts of OAH on the West Coast. The panel's final report, "Major Findings, Recommendations, and Actions," was released in April 2016 and has since generated major interest and action in addressing OAH issues across the region.

One of the panel findings was that the existing water quality criteria for acidification are based on outdated science, as they were developed in the late 1960s and have not been updated since. Recommendation 3 of the panel is the development of new water quality criteria to serve as defined management targets and enable proactive management. In April 2016 the Ocean Protection Council Science Advisory Team convened to review and discuss the panel's final report and highlighted several priority areas of interest for near-term next steps, including Recommendation 3: Revise Water Quality Criteria based on "scientific consensus about which parameters are most appropriate for inclusion." Jonathan Bishop, Chief Deputy Director at the California State Water Resources Control Board, indicated interest in following up on this recommendation.

Subsequent to the panel report, political momentum has increased to support the development of the best science to inform future OA water quality goals. For example, Senate Bill 1363 (SB 1363) establishes an ocean acidification and hypoxia reduction program. Assembly Bill 2139 (AB 2139) authorizes the Ocean Protection Council to develop an ocean acidification and hypoxia science task force and to work with other agencies to coordinate and ensure that water quality goals that address ocean acidification and hypoxia are developed and informed by the best available science. Both bills were signed into law in September 2016.

Meeting Goals and Overview

Building on this momentum, Stanford's Center for Ocean Solutions and the Woods Institute for the Environment partnered with the Ocean Protection Council and the Southern California Coastal Water Research Project Authority to host an Uncommon Dialogue on *Ocean Acidification: Setting Water Quality Goals.* Held on October 17-18, 2016, the meeting brought together 25 experts from the academic, NGO, philanthropic, and California, Oregon, and Washington state and federal management communities to chart a path toward development of new acidification water quality goals and, in the long term, possible criteria. The discussion acknowledged that OA water quality goals are needed in the near term to assess whether marine waters are affected by OA and to interpret output from water quality models that are being developed to support management decisions. In the longer term, these goals could form the foundation for water quality criteria, though there are additional non-technical barriers to regulatory promulgation. Based on this understanding, the workshop focused on three goals:

1) Identify the chemical and biological indicators that are most appropriate for assessing the status of ocean acidification;
2) Prioritize the research needed to advance these indicators toward use as water quality goals; and,
3) Pinpoint the biggest impediments to criteria development and actions that can be taken to lessen these impediments.

The meeting was organized around three sessions that each began with plenary presentations by experts, followed by small group breakout discussions and plenary report outs. Session 1 reviewed the state of the science about which chemical and biological acidification parameters would be most appropriate as OA water quality goals, and what we know about thresholds for each of these parameters. Session 2 evaluated the process and information requirements for establishing OA water quality goals, and prioritized gaps that must be filled to meet those requirements. Session 3 examined impediments water quality managers face in developing improved acidification water quality criteria, with the goal of developing a work plan for filling information gaps and overcoming priority impediments.

Session 1: State of the science: The most meaningful acidification parameters and what we presently know about thresholds

Summary

Session 1 began with a series of overview talks on the state of the science around appropriate acidification parameters and their thresholds. Plenary presentations were given by Francis Chan, Associate Professor, Department of Integrative Biology from Oregon State University, on “Setting ocean acidification water quality goals: Some chemical perspectives” and George Somero, David and Lucille Packard Professor in Marine Science from Stanford University on “Defining ‘thresholds’ for OA effects: mapping chemical parameters to biological responses.” These talks emphasized a huge opportunity for action on this issue, but they also recognized many scientific unknowns. For example, Francis raised challenges regarding our ability to accurately monitor OA impacts, define and detect variability, and deal with multiple stressors. George highlighted the differences, challenges, and value derived from lab versus field experiments that can help develop biologically meaningful and attainable information on OA for use in water quality management.

After the plenary talks, participants were split into two breakout groups — one focused on biological parameters and the other on chemical parameters — that were asked to develop a priority list of parameters on which to focus future research plans. Each breakout group was charged with answering the following questions:

1) If you had to select thresholds today, what are the most appropriate acidification parameters?
2) What do we know about thresholds for each of these parameters?

The group acknowledged the potential for utilizing the parameters and thresholds identified in these discussions for setting water quality criteria over the long term, but also recognized that there is a need in the shorter term to use the identified parameters as assessment end points for coupled bio-physical models, or as targets for monitoring. This session was intended to better inform decisions currently being made by the research and management community with regard to what parameters we should monitor and model.

Session 1 Breakout Findings

Chemical Group

Chemical breakout participants identified **pH** and **carbonate saturation state** as the two parameters that are the most likely candidates for near-term adoption as water quality goals (Table 1). Participants reached this conclusion because these parameters are relatively easy to quantify using available technology, they have been documented through both laboratory and field studies to affect biota, and their widespread use in ongoing monitoring programs provides context for how these parameters vary naturally in the ocean environment. These parameters were also highlighted as being relevant for management in estuarine and/or coastal waters within state jurisdiction. Participants also indicated that identifying a common threshold that accounts for both pH and ~~carbonate~~ aragonite saturation—e.g., a particular pH level that ensures the carbonate saturation state threshold is not surpassed in particular environments—would be valuable.

Parameter	**Threshold**
pH	0.2 deviation from natural
aragonite~~carbonate~~ saturation state	1.6 (protects larval state of calcifiers)

Table 1: Summary of chemical breakout group priority parameters and suggested threshold values.

Before narrowing in on **pH** as a top parameter, participants discussed several candidate primary parameters (those carbonate system parameters that are measured directly), including **pH, *p*CO_2, DIC, total alkalinity, and CO_3^{2-} (carbonate ions).** pH was discussed specifically as a good parameter for assessing OA-related effects for non-calcifying organisms. The group noted that of the current water quality standards in the California Ocean Plan relating to pH, the natural variation range—0.2 pH units different from natural—is probably a good water quality goal for pH, but the absolute pH range in the Ocean Plan—within 6.0 to 9.0 at all times—is too wide a range to protect against harmful effects of OA. There was a great deal of discussion about what a "deviation from

Commented [10]: I would eliminate this table. It's not comprehensive and not defensible based on the rationale in the text.

Commented [11]: The group actually came to the conclusion that this criteria must be further evaluated with additional meta analysis research studies to provide a statistical basis for 0.2 as the agreed upon criteria. Right now it cannot be determined if 0.2 is the optimal criteria.

Commented [12R11]: I agree—it's too early to report out on this group vibe check. Better to support this concept with a review.

Commented [13R11]:

Commented [14]: Some harmful effects have been observed below pH 7.7, for example.

natural" threshold should be and consensus was not reached in the short time. The group agreed that the other primary parameters did not warrant further consideration: there is a lack of information about DIC and CO_3^{2-} effects on organisms, total alkalinity does not have confirmed, clear biological impacts, and finally, while some research suggests that *pCO_2* may positively influence the formation / persistence of harmful algal blooms, evidence is limited. Participants also identified that tools for monitoring of parameters such as DIC, *pCO_2* and CO_3^{2-} were still too early in their development for widespread, routine application by non-specialists.

Commented [15]: I think it's an overstatement that other parameters don't warrant further consideration; better to say that they are not ready for prime time.

Commented [16]: I didn't hear this; I don't think that this is the main point.

Similarly, before prioritizing **carbonate saturation state**, the group considered several candidate derived parameters (those parameters that are calculated from measured primary parameters): **carbonate saturation state (Ω), substrate inhibitor ratios (SIRs),** and the **Revelle factor**. Regarding these derived parameters, the group agreed that carbonate saturation state is the most important for calcifiers. The group proposed a threshold aragonite~~carbonate~~ saturation state of 1.6 as protective of ~~calcifier~~ many calcifying larvae and aragonite saturation of 3.0 for corals. Much discussion ensued regarding the threshold level and agreement about what a threshold should be was not reached. Substrate inhibitor ratios and the Revelle factor were not considered further.

Commented [17]: remove

The group also briefly discussed that the following supporting parameters (those parameters that could influence the carbonate system parameters): **nutrients, pressure, oxygen, temperature, salinity, and calcium ~~cation~~ion concentration**. The group noted that a model output that incorporates these parameters could itself be a water quality goal (e.g., the EPA's Biotic Ligand Model (BLM) or ammonia model); however, the supporting parameters were also not further discussed due to time and the fact that they~~re~~ were not directly related to the group tasks.

Biological Group

Biological breakout participants identified three priority biological organisms whose condition or health could be used as a biological indicator for OA. The group identified **pteropod shell condition** as the most likely biological indicator for near-term application. Pteropod shell condition rose above other candidate biological indicators because it encompassed many of the desirable attributes for selecting candidate biota that the participants discussed. Specifically, pteropods are widely distributed, methods to assess their shell condition are standardized and transferable to non-specialists, and shell condition has been linked to organism growth and survival. In addition, pteropods play an important ecological role as a food source for fish, birds, whales and other organisms, effects of which can be reliably communicated to and understood by the general public. As such, pteropod shell condition represents a measurable early-warning indicator that is predictive of higher-level ecosystem effects. One of the limitations of pteropod shell condition is that they are limited to nearshore and offshore waters, and would be less appropriate for semi-enclosed water bodies (e.g., estuaries or tidepools).

Commented [18]: how about rock fish??

Mussel recruitment and body condition were also identified as strong candidates because mussels are sensitive shell formers that can be easily sampled on either natural or deployable substrates. Mussels also occur close to shore and in estuaries, making them a good range complement to pteropods. While not as naturally abundant and easy to sample as mussels, the participants highlighted that **oysters** show a well-documented response to acidification and are amenable to further laboratory studies that could improve understanding of response. They are also of considerable economic interest.

To select these top candidates, participants focused their discussion around three selection attributes that any candidate biota should have to be considered a priority. They also recognized that there are two ways biology can facilitate the development of water quality goals. The first is by identifying biological responses that are tied to chemical exposure using laboratory and field studies. The second is to use measures of biological community health (for example, benthic infaunal community diversity and function) (as a goal.[1] The group noted that the following three selection attributes applied regardless of which of the two uses of biological information were being considered.

1) **Organism vulnerability to acidification.** The group desired to identify the "canary in the coal mine"—the biotic response that precedes, and is therefore protective of, responses by most other organisms. The primary attribute in this category is sensitivity, which provides a metric for selecting among several possible responses (calcification, dissolution, behavior, survival, growth, reproduction) and life stages. The second key attribute in this category is the organism's inability to acclimatize or adapt to increasing levels of acidity, which must be monitored to avoid underestimating the potential biological responses of more vulnerable species.
2) **Practical considerations.** The group was interested in identifying response organisms that are accessible, sampleable, and easy to identify. They emphasized that candidate organisms need to be abundant in State waters—i.e., within three miles of the coast—where state water quality managers have jurisdiction. They also identified that candidate organisms should have a broad geographic distribution and preferably occur over a range of habitats (e.g., open ocean, nearshore, intertidal, estuarine). Identifying such an organism(s) would help mitigate the need to develop the scientific basis for many organisms, with each specific to a small part of the overall range.
3) **Ease of communication to the public.** The group highlighted that specific effects on the biological indicator must be reliably communicated to and understood by the general public. This could mean that a biological indicator is economically or ecologically important, such as a keystone predator, a habitat former, or a key food web component. While this attribute was considered less important than the organism's vulnerability to acidification, the group recognized that identifying a response that the public could understand would empower managers to use the information to make important and potentially expensive decisions.

In addition to addressing the breakout session's primary charge by highlighting pteropods, mussels, and oysters as priority candidate biological indicators, participants

[1] For example, participants noted that biological criteria are already being used in California as a focal point for sediment quality criteria, in which a healthy benthic infaunal community is the biological expectation.

Commented [19]: We discussed coastal and estuarine habitats as possibly experiencing higher exposure to OAH, and mussels/oysters would provide that range also (not just proximity to shore, but also exposure frequency/duration). May want to include that here, although it may be a nuance.

Commented [20]: I'm not sure I'm following this phrase?

Commented [21]: Selecting indicators based on the hoped-for understanding of the "general public" is a fraught approach as the public generally does not care very much (and many do not even know) about this issue. Finding a charismatic fauna for a public campaign is a different need that doesn't have to be tied to selection of indicators for regulatory purposes. Suggest being much clearer and more specific about the necessary desired audiences for use of indicators and what actions they may need to take, support, etc.

also identified several additional biological responses for possible use as biologically-based water quality goals—those that are prime subjects for calibrating chemical water quality goals and those that demonstrate a high level of promise but would require additional research investment to develop further.

Those candidates that were highlighted as good subjects for calibrating possible chemical goals through additional laboratory and field experiments included **pteropod shell condition** and **oysters** for the reasons identified above. In addition, **rockfish behavior** was reviewed and prioritized because participants were committed to identifying at least one response that was not based primarily on shell-forming ability and evidence suggests that rockfish behavior is influenced by exposure to changes in ocean chemistry.

Finally, participants highlighted three biological responses for potential future use, but which would depend on more research investment to develop further. First, **sea urchin condition** was selected because their distribution has been shown to be affected by acidification and water quality managers already frequently use the sea urchin fertilization test as an effluent assessment technique. Second, the group identified that existing biological criteria in California and the rest of the nation are developed mostly around community-level response, as opposed to individual species responses. Toward that end, they agreed that the **microalgal community** and the **microbial guild** would be one candidate for exhibiting~~the~~ community-level responses ~~that most sensitive to acidification~~. However, participants recognized that because of a high degree of variability in these communities, differentiating natural from affected communities would take at least a decade of research to resolve.

Session 2:
The process and information requirements for setting water quality goals

Summary
Session 2 led with plenary talks on the state and federal perspectives on the process and information requirements for setting water quality goals. Jonathan Bishop, Chief Deputy Director of the California State Water Resources Control Board, gave the California state perspective on "Ocean Acidification: Scientific Challenges and Opportunities for Water Quality Criteria Development" and Dana Thomas, Chief, Ecological and Health Processes Branch Office of Science and Technology, Office of Water, gave the Environmental Protection Agency (EPA) perspective with her talk on "Criteria Development at EPA under the CWA."

Jonathon Bishop noted that California's Ocean Plan currently has water quality criteria for pH—relating to both variance from natural levels and absolute limits—but that the current criteria are ineffective for limiting harmful changes in acidity due to lack of existing information about what constitutes natural variability. While recognizing the need for improvements in these criteria, Jonathon discussed the high information burden for revising or establishing criteria and the lengthy and politicized administrative process that must occur prior to adoption. Dana Thomas echoed Jonathon's remarks regarding the investment of time and resources that must precede adoption of new or revised water

Commented [22]: I'm unaware of this work concerning distribution (but could have just missed the relevant papers). I would agree that urchins have been shown to be sensitive to OA.

Commented [23]: My recollection of Dana's presentation and the discussion following it, is that there is not a viable path revising federal water quality parameters for OAH. Rather, the states revising WQC would be.

quality criteria, and explained the detailed scientific information requirements and procedures for criteria development at the federal level. Jonathon noted that due to these limitations, as well as the global causes of acidification, a change to water quality criteria would likely only be pursued at the state level if tangible improvements in water quality could result from limiting localized terrestrial inputs that exacerbate broader ocean acidification effects.

The group then returned to chemical and biological breakout sessions to build on session 1 discussions regarding existing knowledge about chemical and biological parameters. The primary charge for the session 2 breakout groups was to identify pressing research needs that must be filled in order to meet the information requirements for water quality goal development outlined by the state and federal representatives during plenary. Each group was asked to discuss and prioritize the top research projects that federal, state, and philanthropic funders could support to aid research around the priority parameters and thresholds identified by each group during session 1.

Session 2 Breakout Findings

Both the chemical and biological breakout groups discussed and prioritized similar research needs, including defining natural variability in the parameters, standardizing operating procedures for measuring the parameters, expanding our understanding of the linkages between chemical exposure and biological response, and conducting co-located chemical and biological field measurements.

Chemical Group
Specifically, the chemical group discussed and prioritized the following research questions:

1) **Do model organisms respond to absolute or relative changes in pH and aragonite saturation state, or some combination of both?** The group hypothesized that relative change, rather than absolute change, generally leads to impact, but that an in-depth review of the available literature on this question is necessary. To begin, the group highlighted the need to conduct a meta-analysis of the peer-reviewed and grey literature to define magnitude, duration, and frequency of effects from both pH and aragonite saturation state. Group members discussed the meta-analysis should focus on coastal waters (within California's 3-mile jurisdictional limit) and noted that the analysis would be most relevant if it emphasized the three representative organisms identified as priorities by the biological breakout group— pteropod shell condition, mussel recruitment and body condition, and oysters. Group members also discussed extending this analysis to dissolved oxygen (DO), as concern was raised about the need to better understand impacts of multiple stressors.
2) **What experiments can we develop to fill important data gaps identified in the meta-analysis described in (1)?** The group agreed it is unlikely that the meta-analysis would provide enough information to move forward without additional experimentation. Thus, participants highlighted the need to conduct additional lab

and field experiments to fill any priority knowledge gaps identified through the meta-analysis.

3) **How do we measure and describe natural variability in pH and aragonite saturation state along the coast and what role do models play in describing this?** The group discussed the complexity behind defining natural variability in-depth, and prioritized the need for more research to reflect these nuances given that such a description is essential in implementing both current (as detailed in Table 1) and potential future water quality goals. Complexities and unknowns highlighted by participants that should be addressed included:
   - What is the time period from which we are measuring ‘natural’ variability (e.g., pre- v. post-industrial?, present day?, etc.)?
   - How do we understand and measure natural variability from one location to the next, and within the water column given that we know it can be very localized, stratified, and inconsistent over time?
   - Would reference locations, as have been used with other criteria, work for pH and saturation state? Could we use models to classify variability for different areas along the coast at different times and include sentinel sites representing priority habitat types?
   - When thinking about water quality goals and possible future criteria, do we need a natural variability standard or can we define an absolute range? Could we monitor an indicator species instead of measuring deviation from natural?
4) **What are the standard operating procedures for measuring carbonate parameters (including pH) and deriving aragonite saturation state?** The group stressed the need for technology development and standard operating procedures to facilitate consistent and accurate measurements. New replicable and scalable procedures are necessary for non-specialists who are employed to do routine monitoring and implement criteria and measurements of compliance in the field.

Commented [24]: Wrong focus—see my comments on the executive summary. As stated, this research need is not compelling

Other related questions and issues were discussed, but not prioritized, including how the scientific community could ultimately come together to reach consensus about an OA water quality goal. For example, could the community use a similar approach to the IPCC assessment model to reach a consensus? The group also discussed how such a process could enable the creation of broad-reaching communication mechanisms that OA researchers could rely on to proclaim when a chosen parameter reaches a specific threshold—when ocean chemistry has “tipped” to a point of serious harm to the ecosystem. The group also highlighted the importance of understanding and communicating the location of key OA reference sites (sites that are not impacted by OA and therefore can be used as a baseline) and hotspots (sites that are particularly vulnerable to upwelling or discharges) to help inform where to prioritize management. The topic of source attribution was discussed at length given that California does not want to create water quality criteria if it is determined that localized discharges to the coastline do not significantly exacerbate OA. While the issue was acknowledged, a broader discussion was deferred to session 3, as it represents a large impediment to creating and implementing water quality criteria, but not necessarily to filling needed research gaps with regard to creating OA goals. Finally, there was some discussion of how science could inform permissible thresholds (including magnitudes, durations during which the magnitudes are exceeded, and frequency of exceedance) for chemical parameters. The group agreed that this topic is more related to the Session 3 on barriers for criteria development, but pointed to the potential to look at how thresholds were derived for other contaminants such as fecal indicator bacteria.

Biological Group
The biological group identified and defined the following three research questions that would need to be addressed for the development of any potential biological water quality goals:

Commented [25]: Would there be any value in asking whether indicators might be selected in part based on specific beneficial uses and any related indicators?

1) **What is the reference condition and natural variation from reference?** The group was clear that failure to achieve water quality goals must not result from natural spatial or temporal variation or measurement error in the biological response. Therefore, as discussed by the chemical group, it is necessary to define natural variability and other factors, such as measurement error, that could influence establishment of "normal" and ongoing monitoring of biological responses.
2) **What is the connection between the measured response and population level effects?** The group agreed that for a response to elevate to a water quality goal, there must be clear demonstration that the measured response affects species survival/fitness.
3) **Can we define consistent, repeatable measurement technologies that are feasible to deploy at a regional scale?** As highlighted by the chemical group above, research methods that are deployable by a limited number of specialized researchers and equipment are insufficient. Non-specialists who are employed to do routine monitoring must be able to easily implement research methods and technologies.

The group agreed that the emphasis among these three research needs will differ depending on the potential biological indicators, but that these questions need to be answerable for all biotic responses considered. The group also recognized that addressing these questions requires emphasizing co-location of chemical parameter and biological indicator measurements.

The group also discussed the specific research needs for the three potential biological indicators prioritized in session 1—pteropod shell condition, mussel recruitment and body condition, and oysters—within the context of the three questions outlined above.

For pteropods, the group agreed that question 1 about reference condition and natural variation was the most important, as more extensive work has been done to-date on answering questions 2 and 3 regarding this biotic response. They proceeded to recommend the following three high priority studies:

1) Establish a monitoring program that provides co-located chemical and biological measurements over 5 or more years to establish the natural spatial and temporal variability in pteropod density and shell pitting and the chemical parameters pH and ~~carbonate~~ aragonite saturation.

2) Use stored samples or sediment cores to establish historical levels of pitting in pteropod shells. This study would have a goal of establishing natural temporal variability of pteropod density and shell pitting. The group was clear that they were interested in the natural level of variability in present times, not during the pre-industrial period.
3) Conduct bioenergetics studies that quantify the costs to the pteropod for having to continually repair its shell at different levels of acidification exposure.

For oysters and mussels, the group prioritized research questions 2 and 3 about sampling methods and relationship to fitness, and developed the following four research questions for both species:

1) As with pteropods, establish a monitoring program that provides co-located chemical and biological measurements over 5 or more years to establish their natural spatial and temporal variability.
2) Determine which metrics (e.g., growth rate, calcification, respiration, dissolution, etc.) are most sensitive to acidification. Conduct these as comparative studies between/among oyster and mussel species to determine which is most sensitive.
3) Develop consistent, repeatable measurement methods for the most sensitive metrics.
4) Develop connections between the most sensitive measurement parameters and population level effects.

Session 3:
The greatest impediments to criteria development

Summary
The third and final session focused on impediments to targeted research and criteria development and ideas for overcoming those impediments. Caren Braby, Manager, Marine Resources, Oregon Department of Fish & Wildlife, Rochelle Labiosa, Scientist, Water Quality, Environmental Protection Agency, and Miyoko Sakashita, Oceans Director, Center for Biological Diversity shared their reflections in plenary on where we might see the greatest impediments to criteria development moving forward, even if all the necessary scientific research is conducted. Each speaker provided their perspectives and context as state, EPA-regional and NGO representatives.

Each speaker noted that prioritizing action and funding to address ocean acidification requires the attention and support of the public at a time when many other important issues are competing for attention. Other key barriers identified included limitations in government budgets and staff capacity, the high evidentiary and informational burdens, and the lengthy public engagement and procedural process required to develop criteria.

The two culminating breakout groups focused on next steps in criteria development and impediments to progress both within California and at the west coast and federal scales. For this session, the larger group was divided into one group comprising California representatives and a second that included the rest of the meeting attendees (i.e., those from Washington, Oregon and the Federal Government). The primary charge for both groups was to discuss impediments, some technical and some not, and then identify the actionable next steps that would lessen these impediments. Both groups were asked to specifically detail what could be accomplished over what timeframes, and to match key actions to resource needs and timelines. In the discussions the group identified the biggest impediments to moving forward and set a reasonable timeline to address them with a goal towards revising water quality criteria for ocean acidification.

Session 3 Breakout Findings

California Group
The California group grounded their discussions by first recognizing that the state is well positioned to lead the effort on OA criteria development. The Ocean Protection Council has allocated funding to help start the OA criteria revision process and the State Water Resources Control Board expressed interest in revising the criteria if the science was adequate to support a change. For the California delegation of scientists, managers, funders, and NGOs, the most obstructive impediments to moving forward were:

1) **Verification that local sources and inputs are a meaningful contributor to local ocean acidification** and that criteria development and its protracted timeline is worth the investment.
2) **The need for sustained—and increasing—funding sources** that can match the resources necessary to fulfill scientific and regulatory procedural requirements. Across the state and federal governments, funding that supports these and similar science-based regulatory processes is in strong competition with other efforts, and is therefore either expiring or flat-lined annually.
~~2)~~
3) Lack of knowledge on the **natural variability of pH and ~~carbonate~~ aragonite saturation** in state waters.

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The group landed on these top three impediments by voting from a longer list of impediments. There was overwhelming consensus that these were the top three because without overcoming these challenges, we would either be unable to move forward with criteria development or would not feel compelled to initiate the long process of revising criteria. For example, without being able to define or adequately measure deviation from natural variability in the highly variable California Current (impediment 3 listed above), managers will lack information necessary to justify the potentially lengthy, cumbersome, and politically-charged criteria revision process.

The group proceeded to identify what is already being done or can be done to work past the top three impediments, including an existing regional investment in a model to verify local sources of OA (impediment 1).[2] In the next year or two this model will provide estimates of the extent to which local sources and land-based nutrient loading contribute

[2] The Ocean Protection Council, along with the National Oceanic and Atmospheric Administration (NOAA), has recently invested in a regional model hosted by University of California, Los Angeles who is partnering with the Southern California Coastal Water Research Project, the University of Washington, and NOAA-Pacific Marine Environmental Laboratory.

to a worsening of local acidification conditions. A critical next step will be interpreting model results to decide whether to move forward with criteria revision. The timeline for this effort would culminate with summarizing model results by 2019.

Regarding dedicated funding (impediment 2), the group discussed the ~~best case scenario~~potential utility of ~~new~~ state legislation that ~~mandates~~ clarifies any needs for water quality criteria revision and, depending on such needs, allocates new funding and dedicated resources for the effort. The group also stressed the need for more tightly interwoven state and federal funding goals and parallel, transparent, and well-vetted processes for these efforts. For ~~the legislative effort timeline~~potential legislative efforts, the group discussed a tentative goal of ~~passage~~ advancing new policy and funding by ~~September~~ the end of 2018, with ~~broad~~ a need to begin identifying and engaging with supportive constituencies in the near future ~~weighing in, advocating, and coordinating before and after legislation~~. The group also discussed the importance of decision-maker education and outreach undertaken in partnership with affected constituents such as oyster growers and seafood companies.

To determine how to measure and describe natural variability in pH (impediment 3), the group reiterated the need to conduct the research studies outlined by the chemical breakout group. The group confirmed the importance of conducting a meta-analysis to illustrate how organisms respond to absolute and relative changes in pH and aragonite saturation state. The group also recognized the importance of identifying how to measure and describe natural variability in pH and interpret natural conditions as written in California's existing pH criterion.

Oregon, Washington, and Federal Government Group
The breakout group comprising representatives from Oregon, Washington, and the Federal Government agreed that the top impediments to water quality criteria revisions are:

1) **Clearly defining the need to act, the roles, and the action path for all audiences** (e.g., federal, state, industry, NGO).
2) **Developing the necessary science** to support an actionable path to beneficial outcomes (i.e., directly connected to species and ecosystems of concern).
3) **Defining the possible beneficial outcomes**.

With regard to impediment 1, the group highlighted large variation in water quality problems and political will across the region and country. This variation is tied closely to differences in how the issues are prioritized across different geographic scales. Additionally, because of the varying timelines on which states, regions, and groups want to act, the group agreed there is not consensus on how acidification issues should be addressed (e.g., implement OA water quality criteria under the Clean Water Act or pursue some alternative method).

With regard to impediment 2, the group noted that short-term research that quantifies natural spatial and temporal variability across habitats could improve the implementation of existing water quality criteria for relative changes in pH while revised criteria are developed. In addition, the group noted that public support for action depends on establishing and communicating clear scientific linkages between potential regulatory efforts and beneficial outcomes for the species and ecosystems that people care about across the region.

Related to this, the group developed consensus around the need to define the beneficial outcomes of revising water quality criteria (impediment 3). Specifically, scientists and managers must pinpoint how criteria revision could help protect regionally important species that are vulnerable to OA. Building on this, the group identified the need for tools that help the public visualize how OA affects important species and places. For example, the group raised the idea of developing annual ocean acidification stories or report cards for the west coast states that outline how OA is affecting the region today and highlight governmental actions that can be taken to mitigate ocean acidification. The group agreed that this type of public outreach product would help contextualize and illustrate the effects of OA on the highly dynamic California Current System for the public and decision makers alike, and help justify ongoing research and requests for necessary future funding.

With regard to timing, the group noted the importance of pursuing parallel pathways to address OA given the protracted timeline and scale of effort required to revise water quality criteria. The implementation of these endeavors will depend upon the progress made within California in the next several years. Other states and the federal government look to California to assume a leadership role in the effort to develop OA water quality criteria and recognize that a future coordinated response across the regions will be the most impactful. In 2017 and beyond, the group highlighted the need for significant improvement to regional and national monitoring networks (ensuring that there is long-term coupled biological and chemical monitoring), significant investments in monitoring efforts, clear protocol about what to measure and how, and open access information products that share the west coast OA story across the region and country.

Appendix A

Ocean Acidification: Setting Water Quality Goals
Uncommon Dialogue
October 17-18, 2016
Stanford University, Jen-Hsun Huang Engineering Center, Room 305

Hosted by:
Stanford University's Woods Institute for the Environment and the Center for Ocean Solutions, the California Ocean Protection Council, and the Southern California Coastal Water Research Project

Meeting Goals:

- Initiate a process for identifying appropriate chemical and biological indicators and thresholds to assess ocean acidification.
- Identify priorities for short-term research needed to support criteria development.

Monday, October 17

12:00 – 1:00 PM	Check-in and lunch
1:00 – 1:45 PM	Welcome, introductions, workshop goals and agenda review
1:45 – 2:45 PM	**Plenary Session 1**: State of the science: The most meaningful acidification parameters and what we presently know about thresholds *Francis Chan – An introduction to potential chemical indicators* *George Somero – A mapping of chemical parameters to biological responses*
2:45 – 3:00 PM	Introduce breakout session 2 and take a break
3:00 – 4:30 PM	**Breakout Session 1:** If you had to select thresholds today, what are the most appropriate acidification parameters and what do we know about thresholds for those parameters? *Group A: Chemical parameters (Room 305)* *Group B: Biological parameters (Room 306)*
4:30 – 5:15 PM	Breakout group report out and discussion
5:15 – 5:30 PM	Close and overview of Day 2

5:30 – 7:00 PM	**Dinner:** Group shuttle to Spalti Ristorante, 417 California Ave, Palo Alto

Tuesday, October 18

8:00 – 9:00 AM	Breakfast
9:00 – 9:15 AM	Overview of the day and questions
9:15 – 10:15 AM	**Plenary Session 2**: The process and information requirements for setting water quality criteria *Jonathan Bishop - State of California perspective* *Dana Thomas – EPA perspective*
10:15 – 10:30 AM	Introduce breakout session 2 and take a break
10:30 – 12:00 PM	**Breakout Session 2:** What are the greatest research needs to improve our use of thresholds and to create a path toward criteria? *Group A: Chemical parameters (Room 305)* *Group B: Biological indicators (Room 304)*
12:00 – 12:30 PM	Break, get lunch, reconvene
12:30 – 1:30 PM	**Working lunch**: Breakout group report out and discussion
1:30 – 2:30 PM	**Plenary Session 3**: The greatest impediments to criteria development *Caren Braby – State perspective* *Rochelle Labiosa (invited) – EPA regional perspective* *Miyoko Sakashita – NGO-legal perspective*
2:30 – 2:45 PM	Introduce breakout session 3 and take a break
2:45 – 4:00 PM	**Breakout Session 3:** Development of a roadmap, timeframe, and next steps *Group A: California participants (Room 304)* *Group B: Federal and regional participants (Room 305)*
4:00 – 4:45 PM	Breakout group report out and discussion
4:45 – 5:15 PM	Next steps and wrap up
5:15 – 6:30 PM	**Reception:** Faculty Lounge, Y2E2 Third Floor

Appendix B

Ocean Acidification: Setting Water Quality Goals
Uncommon Dialogue
October 17-18, 2016
Stanford University, Jen-Hsun Huang Engineering Center, Room 305

Participant List

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